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ATMOSPHERIC, CLIMATIC, AND ENVIRONMENTAL RESEARCH

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INTRODUCTION

Columbia University has engaged in a program of research in climate modeling, stratospheric and tropospheric research, climate applications of earth observations, and chemistry of earth and environment in close association with the scientific and technical staff of NASA Goddard Space Flight Center, Institute for Space Studies (GISS). The joint research programs have been carried out over an eleven-year period between Oct. 1, 1983 and Dec. 31, 1994.

The collaboration between Columbia University and GISS under this cooperative agreement has proceeded on a number of levels. Graduate students and research associates at the University constituted a large part of the manpower working on many climate, planetary and environmental problems pursued by the Goddard Institute, and in course of conducting this research they made heavy use of the Institute's computational facilities. Scientists at the Institute in turn have taught courses at the University and have acted as research sponsors for graduate students in the departments of Geological Sciences, Applied Physics and Nuclear Engineering, and Physics. Substantial scientific interaction and collaboration has occurred between senior scientific personnel at Columbia and GISS in defining and carrying out the research projects.

While the various projects are identified separately, in this report, for purposes of description and classification, there has often been a close interaction among them, particularly on the theoretical side; where this has occurred, the necessary coordination was provided by the Columbia faculty and the staff of the Goddard Institute.

The following pages briefly describe some highlights of the research accomplished by the various disciplines over the period of the cooperative agreement.

TASK A: CLIMATE AND ATMOSPHERIC MODELING STUDIES

SUMMARY

The climate and atmospheric modeling project involves analysis of basic climate processes, with special emphasis on studies of the atmospheric CO₂ and H₂O source/sink budgets and studies of the climatic role of CO₂, trace gases and aerosols. These studies are carried out, based in part on use of simplified climate models and climate process models developed at GISS. The principal models currently employed are a variable resolution 3-D general circulation model (GCM), and an associated "tracer" model which simulates the advection of trace constituents using the winds generated by the GCM.

CLIMATE MODEL DEVELOPMENT AND APPLICATIONS

The research in the climate and atmospheric modeling programs has concentrated on the improvement of atmospheric and upper ocean models, and preliminary applications of these models. Principal models are a one-dimensional radiative-convective model, a three-dimensional global climate model (GCM), and an upper ocean model.

An efficient, variable-resolution GCM has been developed at GISS for the study of climate and climate change. The GCM solves the equations of conservation of mass, momentum, heat and water vapor in the atmosphere. The local sources and sinks of these conservative quantities are parameterized in a realistic fashion to interact with climate change. At its lower boundary, the atmosphere exchanges heat and moisture with the upper ocean and with the ground. In the current version of the GISS GCM (Hansen et al., 1983, 1988), the seasonally varying mixed-layer depths of the ocean are prescribed, and the horizontal divergence of heat transport implied by the model are included. Some of the key improvements which have been added to the GCM during the period spanned by this cooperative agreement were developed by Columbia personnel. These include: 1) modeling of the ocean and ocean ice processes, 2) development of a physically more realistic treatment of atmosphere-land surface processes, and 3) use of an isotopic tracer model to track water vapor transport in the model.

Principal applications have been the study of the impact of CO₂, aerosols, and the solar 'constant' on climate. Progress has been made in the 3-D model development towards physically realistic treatment of these processes. In particular, boundary layer, land surface convection, and large-scale cloud schemes have now been incorporated into the GISS GCM. Professor Douglas Martinson, Columbia University, has assisted in the development of sea-ice models and air-sea interaction. Other Columbia University contributions have been made by Prof. Arnold Gordon and Dr. Mark Cane, who have worked on ocean circulation and atmospheric-ocean modeling. In addition, Columbia University graduate research assistants and undergraduate student programmers have also contributed substantially to the project.

Climate research focuses on the development of the next version of the GISS GCM: model III. A ground hydrology scheme has been incorporated into the model. New convection and large-scale cloud schemes have been evaluated and refined. The model has been run with these, and additional improvements and corrections have been made.

Testing of the new convective scheme in the GCM has shown improvements over Model II in upper troposphere and boundary layer humidity. An analysis of the new model's tropical variability suggests an increase in the vigor of convective storms in a warmer climate, but to a lesser extent than implied by more limited analyses of tropical radiosonde profiles.

Modeling of the climate and vegetation change of the last 30,000 years, and of the Little Ice Age, has been undertaken, in order to compile plausible boundary conditions for GCM runs. Statistical and process-oriented models were used to simulate climate-induced vegetation changes that took place over the last glacial to interglacial transition (18,000 years ago to present). GISS and NCAR GCM simulations of past climates were input into vegetation models and resulting vegetation changes were compared to those reconstructed from a network of over 250 radiocarbon-dated pollen records from eastern North America. These models were then applied to the simulated equilibrium climate change that could be expected within the next 200 years, due to greenhouse-gas warming. The results suggest that future vegetation changes could be

unprecedented in both size and rate. Significant changes could occur as early as the first quarter of the next century.

Sensitivity studies of North Pacific sea surface temperatures (SST) to global climate change continue. The results of the North Pacific cooling experiment have significant implications for northern hemisphere temperature depression, as well as ice sheet growth.

A two-hemisphere sector ocean model, with mixed surface boundary conditions, has been used to examine the long-term (15,000 years) natural variability of the oceanic circulation. In two runs, with varying temperature relaxation time scales, the enhanced North Atlantic Deep Water (NADW) occurs simultaneously with enhanced sinking in the deeper levels of the southern hemisphere (Antarctic Bottom Water). The NADW increase is produced by increased advection of saline water to the high northern hemisphere latitudes; the enhanced sinking of the AABW at deeper levels is produced by cooling of the southern hemisphere high latitude waters. In other runs, the latitudinal distribution of fresh water flux is changed, holding the global average constant. Here, the main variation is in the increase of the Antarctic Bottom Water, and the decrease of North Atlantic Deep Water.

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CLIMATE, OCEANS AND CO₂ STUDIES

One of the important research objectives involves the application of the GCM and tracer models to study the effects of the increasing atmospheric CO₂ and its sources and sinks, particularly with respect to the biogeochemical cycles of CO₂. The 3-D general circulation model has been employed to investigate the contribution of different physical processes to climate maintenance and climate change. The GCM output has furthermore been used to evaluate the impact of climate change on the habitability of the planet.

The ocean plays a critical role in the determination of the climate of the atmosphere, as well as in the timing of climate change. The current GCM used in the simulation of equilibrium and transient climate of the atmosphere employs a highly parameterized ocean in which lateral transports of heat are held constant at current values. The development of an interactive dynamical ocean general circulation model for coupling with the atmospheric GCM continues. Dr. Garraffo (former Associate Research Scientist, Columbia University), in collaboration with Dr. Inez Fung (former GISS scientist) has performed a series of numerical experiments addressing conditions under which decadal variability appears in the two-hemisphere sector ocean model.

PALEOCLIMATES

The paleoclimate project involved pollen and macrofossil studies in conjunction with GISS GCM studies of paleoclimate. Dr. D. Peteet (GISS) was the Principal Investigator. Sample cores for pollen and macrofossil analysis have been collected from the northeastern U.S., the southeastern U.S. Alaska, and Russia. Evidence for the Younger Dryas climatic oscillation (11,000-10,000 years BP) was found in several northeast U.S. cores. In these cores, rapid climatic oscillations were detected--too rapid to be explained by Milankovitch cycle forcing. The vegetational and sedimentological analyses of three northeastern United States wetland sites, documenting the regional vegetational, fish, and climatic history over the last 12,400 years, has shown an extremely rapid response to climate change, which parallels the climate change itself (as measured independently in Greenland ice cores). This result is significant for two reasons:

- 1) Biologists concerned about future greenhouse warming have believed that the anticipated rapid and large climatic warming has had no analog over the last 100,000 years. This research provides evidence that a 3-4°C warming has occurred in the northeastern U.S. in as short a time as 50-100 years.

- 2) Ecologists concerned about vegetational responses to climatic change considered trees to have a long migration response time. Our research shows that the vegetation change took place within 50 years.

The timing and direction of climate change, from the Last Glacial Maximum (LGM) into the Holocene was investigated at a new site in the North American central Appalachians (Brown's Pond, Virginia), which dates to 17,130 C¹⁴ years BP. Post-glacial cold reversals in the core are centered at 12,240 and 7500 C¹⁴ yr BP, paralleling Greenland ice core coolings. A new simulation of the Ice Age climate with Model II of the GISS GCM resulted in much colder air temperatures than previous Ice Age runs. This modeling research was performed in collaboration with Dr. David Rind, Dr. Tony DelGenio, and Dr. Dorothy Peteet (GISS Staff Scientists).

Collaboration with Dr. Andre Andreev, a GISS NRC post-doc, involved comparison of high latitude changes in Siberia with those from Alaska and Canada, to develop a comprehensive northern hemisphere perspective. A long-term Arctic record of peatland dynamics, vegetation, and climate history of the Pur-Taz region, western Siberia, demonstrated changes in climate throughout the Holocene. Of particular significance is the evidence for old ages of uppermost peats in the region, suggesting either a real lack of peat accumulation in recent millennia, or recent oxidation of uppermost peat.

Field and data analysis on Kodiak Island, Alaska (in collaboration with Dr. Dan Mann, University of Alaska) has outlined the history of glacial expansion and retreat on the western side of this island. The detailed late-glacial vegetational history has revealed a dramatic late-glacial oscillation in western Kodiak, which parallels the younger Dryas event of the circum-North Atlantic region. A possible scenario for this change has been modeled, relating to sea surface temperatures in the North Pacific. A large Northern Hemisphere temperature and snow cover response has been found.

GCM modeling of the last glacial maximum as well as the late-glacial and early Holocene intervals has been undertaken, using the GISS GCM Model II'. One focus of the paleoclimate modeling program has been on the Little Ice Age, in an effort to understand the natural forcing (e.g. solar, volcanic, and thermohaline) behind decadal to century-scale climatic variability. Dr. D. Rind (GISS) has collaborated with Drs. Peter DeMenocal, Richard Fairbanks, and Douglas Martinson (Lamont-Doherty Earth Observatory) on this project.

Paleoclimate research continues to test the ability of the model to produce reasonable estimates of the deglaciation of the last ice age, in order to compare its sensitivity with that of the real world. An additional component incorporated into the ocean model includes an upper ocean/sea-ice model developed by Dr. Douglas Martinson of Lamont-Doherty Earth Observatory, and the numerical ocean model designed by Dr. Gary Russell of GISS. On a broader scale, in cooperation with Lamont scientists, efforts have been made to model the global extent of the Little Ice Age (circa 1700 A.D.). Modeling studies were performed to test various forcing mechanisms for Little Ice Age climate change, and the results were compared to existing observations from that time period (e.g. tree rings, corals, historical records, etc.). This research was also conducted in cooperation with Dr. Gordon Jacoby, LDEO.

CLIMATE IMPACTS

Sea Level Rise Impacts

A digitized coastal hazards data base was developed by V. Gornitz (Columbia University) for the conterminous United States, which can be used to assess coastlines at risk to sea-level rise. The database consists of information on elevation, geology, geomorphology, sea-level trends, shoreline changes, tidal ranges, and wave heights. These variables were assigned risk values on a scale from 1 to 5 (5 being the highest risk) and integrated into a Coastal Vulnerability Index (CVI). The CVI has been used to identify high risk areas along sections of the East Coast, including parts of Long Island, the New Jersey barrier beaches, the North Carolina Outer Banks, the southern Delmarva peninsula, and parts of Georgia-South Carolina. Other high-risk areas include the Louisiana-Texas coast and the Sacramento-San Joaquin Delta, California. An expanded CVI, including 6 climatological variables, was applied to an assessment of the biogeophysical vulnerability to sea-level rise in the southeastern U.S.

Methane Release from Methane Hydrates

A warmer future climate could hasten the decomposition of methane hydrate from permafrost and deep-sea sediments, thus increasing atmospheric methane. Oceanic methane hydrate reservoirs have been estimated by Dr. V. Gornitz and Dr. Inez Fung (GISS), based on two proposed models: a) in situ-bacterial formation and b) pore fluid-migration. The most likely range of methane volumes was found to be $0.6-1.2 \times 10^{16} \text{ m}^3$, which lies toward the lower end of recent published estimates. Although both models predict similar methane volumes, they differ significantly in atmospheric methane release. A uniform depth distribution of hydrate beneath the seafloor (as in model a) could potentially release more methane, as the ocean warms within the next 100 years, than concentration near the base of the hydrate stability zone (model b).

Sea Ice Variability

Sea ice variability on decadal time scales was analyzed from the Walsh data set, covering the period 1953-1990, for the Northern Hemisphere, and 1973-1990, for the Southern Hemisphere. The effect of grid cell resolution and boundary threshold on sea ice area, extent, and open water (within the ice area) was investigated. Average hemispheric and 30° longitudinal sector seasonal cycles and time series were determined, in addition to long-term changes in duration of the ice-free period and in an area of open water within the ice. Tests were made for interannual variability and persistence, as well as correlations between hemispheres, and also correlations with SST data sets.

The areal extent of sea-ice revealed high interannual spatial variability and high sensitivity to climate forcing. Any appreciable changes in sea ice areal extent could significantly impact climatic and oceanic conditions (affecting albedo feedbacks, heat, kinetic energy, water vapor and salt exchanges). The results from this study, conducted by Dr. V. Gornitz (Associate Research Scientist, Columbia University) in collaboration with Dr. David Rind (GISS) and Dr. Mark Chandler, have provided more realistic boundary conditions for climate model experiments.

SAGE II AND STRATOSPHERIC MODELING

A group of Columbia and GISS scientists have participated in the SAGE II experiment to determine vertical profiles of ozone and aerosols throughout the stratosphere. The experiment was launched in October 1984.

A series of experiments has been conducted to explore the connection between UV variations associated with the solar cycle and the troposphere/stratosphere system. These experiments were designed to test whether:

- 1) there is any systematic UV influence on tropospheric processes;
- 2) the influence differs when the QBO is in the east phase versus the west phase;
- 3) there are any seasonal differences in the tropospheric response (for example, Labitzke and van Loon found the largest tropospheric impact during winter);
- 4) the stratospheric responses compare well with observations (which again vary seasonally);
- 5) the mechanisms involved in any observed interactions.

In the final series of experiments, the solar UV forcing has been reduced to be more consistent with observations. In particular, a subset of these experiments was run with a $\pm 5\%$ change. Subsequently, the increase was varied as a function of wavelength.

A three-year portion of the control run was run with a $\pm 25\%$ change in UV radiation ($< 0.3\mu$). Inasmuch as the effect of solar activity variations is apparently observed more clearly when modulated by the phase of the Quasi-Biennial Oscillation (QBO), in the first experiment, a QBO was induced in the model, by using an additional momentum forcing in the lower stratosphere to produce either strong tropical east winds or west winds (the model under normal circumstances does not generate a QBO, perhaps because of insufficient resolution). Two Quasi-Biennial Oscillation (QBO) simulations were run for a three year period, and then repeated with the $\pm 25\%$ change. Then a set of initial conditions (outside the tropics) which had produced a stratospheric warming in the control run was re-introduced. The model generated a strong warming in the QBO east phase, but not in the west phase. This was the result of increased upward wave activity flux from mid-latitudes during the QBO-east. The tendency for warming

mainly during the east phase is in agreement with observations. These experiments suggest that the model is able to differentiate dynamic events in its different QBO phases despite the artificiality of the QBO generation (Balachandran et al., 1992).

In the next experiment, using the control run, the UV radiation below 0.3μ was changed by $\pm 25\%$, and also by $\pm 10\%$ and $\pm 5\%$. This follows the general modeling approach: first use strong forcing to elucidate mechanisms, and see if there is any response, then reduce the forcing back to realistic magnitudes.

The experiments were then repeated with both east and west wind phases of the QBO. Results showed that during periods of increased UV radiation, the west wind QBO phase experienced warming in the winter polar stratosphere, while during periods of reduced UV radiation, the east wind QBO phase in the same region experienced warming. This agrees with observations, and is associated with changes in energy propagation into the stratosphere and changes in propagation conditions in the stratosphere.

TASK B: CLIMATE APPLICATIONS OF EARTH AND PLANETARY OBSERVATIONS

CLOUD CLIMATOLOGY

This project involved development of new techniques and radiative transfer models to analyze satellite observations of clouds and the surface of the earth for climate studies. Dr. Leonid Garder (former Senior Research Staff Associate) had primary responsibility for Columbia's part of the program. In addition to Dr. Garder, the cooperative agreement supported Dr. Y. Zhang (Senior Research Staff Associate), two visiting scientists (G. Seze, L. Machado), six post-doctoral researchers (B. Carlson, M. Allison, G. Tselioudis, X. Liao, and B. Cairns), and six Ph.D. students (L. Smith---1987, R. Fu--1991, G. Tselioudis--1992, Q. Han--1992, B. Lin--1994, J. Wang--1995). Columbia graduate and undergraduate students have provided some programming assistance, part-time during the academic year and full-time during the summer.

This research utilized cloud and surface remote sensing techniques as part of the International Satellite Cloud Climatological Project (ISCCP) and the Surface Radiation Budget Project (SRBP), the U.S. national contribution to ISCCP, the First ISCCP Regional Experiment (FIRE), and the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Region Experiment (TOGA-COARE). The Columbia efforts focused on diagnoses of the meteorological processes that determine cloud properties.

The research involved investigation into the following:

- 1) Examination of the properties of cirrus clouds inferred from satellite imaging radiometers (ISCCP) and infrared sounders (HIRS).
- 2) Study of long-term statistics of tropical convective systems, including determinations of size distributions and lifetimes using ISCCP data.
- 3) Analysis of synoptic-scale relationships of cloud properties and their variations with mid-latitude meteorology.

The research covered under this cooperative agreement resulted in 40 publications between 1984 and 1995. A summary of accomplishments during this period includes the following:

- 1) Development of comprehensive cloud analysis methods for the application to meteorological satellite observations.
- 2) The first comprehensive analysis of the cloud properties of Jupiter (see also under Planetary).
- 3) Development of comprehensive methods for determining the evolution of tropical convection from satellite observations.
- 4) The first global survey of cloud particle sizes.
- 5) The first estimates of ice cloud water amounts.
- 6) The first comprehensive global calculations of the Earth's radiation budget based on observed cloud, atmosphere, and surface properties, that evaluates the combined effects of clouds on top-of-atmosphere, surface, and in-atmosphere radiative fluxes.
- 7) The first global analysis of cloud vertical structure.

PLANETARY STUDIES

Planetary studies have been supported by Galileo Project funding of GISS data analysis (UPN 889). Columbia students have conducted graduate research and provided programming support for this project.

Galileo cruise observations of Venus and Earth were analyzed using multiple scattering models and the Venus results were compared with Pioneer Venus data.

RADIATION

One GRA (Fan Xu) in the Radiation program was supported by the NASA-Lamont cooperative agreement. Fan studied the uncertainties associated with the calculation of the earth radiation budget from satellite data. Fan used the GISS GCM to estimate the uncertainties associated with the conversion of broad- and narrow-band radiances into fluxes. The results of this study have shown that greater uncertainties result from the narrow band-radiance to flux conversion than with the broad-band radiance to flux conversion. In both cases, the presence of

optically thin and overlapping clouds account for most of the uncertainty introduced into the flux conversion. The research was continued, conducting a comparison of the earth's radiation budget from the GISS GCM with ERBE satellite measurements.

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TASK C: CHEMISTRY OF EARTH AND ENVIRONMENT.

The monies that went to Lamont-Doherty were used to support graduate student research for projects with bearing on global change. Major accomplishments are as follows:

1. SOIL WEATHERING: ROBERTO GWIAZDA.

- a. Gwiazda, R.H., and W.S. Broecker, *The separate and combined effects of temperature, soil $p\text{CO}_2$ and organic acidity on silicate weathering in the soil environment: Formulation of a model and results*, Global Biogeochemical Cycles, **8**(2), 141:155, 1994.

Abstract. A model is used to evaluate the relative importance of temperature, soil $p\text{CO}_2$, and organic acidity on silicate weathering rates in an average soil of warm temperate climate. The model has a structure similar to the Model of Acidification of Groundwater in Catchments, (Cosby et al., 1985a, b)^{1,2} used to predict catchment responses to acid deposition, but it is modified to account for the effects of temperature, the partial pressure of carbon dioxide in the soil, and organic acidity on dissolution of silicate minerals. The model is run with a mean soil temperature of 15°C, and when equilibrium is achieved it is raised to 19°C. Soil $p\text{CO}_2$ and organic acids adjust accordingly. It is found that temperature is the main control of the weathering rate; the other two factors have a very minor forcing effect. The transient after the step function disturbance occurs on a century to millennial timescale. Consequently, it is not possible to study weathering rates through either purposeful soil manipulations lasting several years or by examining the effect on soils of land use changes because steady state may have not been achieved yet.

¹ Cosby, B. J., G. M. Hornberger, and J. N. Galloway, Modeling the effects of acid deposition: Assessment of a lumped parameter model of soil water and streamwater chemistry, *Water Resour. Res.*, **21**, 51-63, 1985a.

² Cosby, B. J., R. F. Wright, G. M. Hornberger, and J. N. Galloway, Modeling the effects of acid deposition: Estimation of long term water quality responses in a small forested catchment, *Water Resour. Res.*, **21**, 1591-1601, 1985b.

2. PALEO PH RECONSTRUCTION: ABHIJIT SANYAL.

- a. Sanyal, A., N.G. Hemming, G.N. Hanson, W.S. Broecker, *Evidence for a higher pH in the glacial ocean from boron isotopes in foraminifera*, *Nature*, **373**, 234:236, 1995.

Abstract: Records of past changes in the pH of the oceans should provide insights into how the carbonate chemistry of the oceans has changed over time. The latter is related to changes in the atmospheric CO₂ content, such as that which occurred during the last glacial-interglacial transition³. Previous studies^{4,5} have shown that the fractionation of boron isotopes between sea water and precipitated carbonate minerals is pH-dependent. This finding has been used to reconstruct the evolution of ocean pH over the past 20 million years by analyses of boron isotopes in the carbonate shells of foraminifera⁶. Here we use the same approach to estimate changes in ocean pH between the last glacial and the Holocene period. We estimate that the deep Atlantic and Pacific oceans had a pH 0.3 ± 0.1 units higher during the last glaciation. The accompanying change in carbonate ion concentration is sufficient to account for the decrease in atmospheric Pco₂, during the glacial period³. These results are consistent with the hypothesis⁷ that the low CO₂ content of the glacial atmosphere was caused by an increased ratio of organic carbon to carbonate in the 'rain' to the sea floor, which led to an increase in carbonate ion concentration (and thus in pH) of deep water without a corresponding increase in the lysocline depth.

- b. Sanyal, A., N.G. Hemming, W.S. Broecker, D.W. Lea, H.J. Spero, and G.N. Hanson, *Oceanic pH control on the boron isotopic composition of foraminifera: Evidence from culture experiments*, *Paleoceanography*, **11(5)**, 513:517, 1996.

³ Neftel, A., Oeschger, H., Staffelbach, T. & Stauffer, B. *Nature* **331**, 609-611 (1988).

⁴ Vengosh, A., Kolodny, Y., Starinsky, A., Chivas, A. R. & McCulloch, M. *Geochim. Cosmochim. Acta* **55**, 2901-2910 (1991).

⁵ Hemming, N. G. & Hanson, G. N. *Geochim. Cosmochim. Acta* **56**, 537-543 (1992).

⁶ Spivack, A. J., You, C.-F. & Smith, H. J. *Nature* **363**, 149-151 (1993).

⁷ Archer, D. & Maier-Reimer, E. *Nature* **367**, 260-263 (1994).

b. Sanyal, A., N.G. Hemming, W.S. Broecker, D.W. Lea, H.J. Spero, and G.N. Hanson, *Oceanic pH control on the boron isotopic composition of foraminifera: Evidence from culture experiments*, *Paleoceanography*, **11**(5), 513:517, 1996.

Abstract. Culture experiments were carried out with the species *Orbulina universa* at four different pH values (7.70 ± 0.05 , 8.15 ± 0.05 , 8.60 ± 0.05 , and 9.00 ± 0.10) in order to establish the pH-dependence of boron isotope fractionation between seawater and foraminifera. A clear relationship between the boron isotopic composition of the foraminifera and the pH of the seawater culture solutions was found, showing heavier boron isotopic composition at higher pH. This finding supports the viability of boron isotopes as a paleo-pH tool. It is important to note that *Orbulina universa* cultured in natural seawater, as well as those obtained from coretop samples, have a significantly lighter boron isotopic ratio than *Globigerinoides sacculifer* from coretop samples, suggesting that at least for this species, a vital effect is active.

3. LONG DISTANCE WATER VAPOR AND IMPLICATIONS TO OCEAN THERMOHALINE TRANSPORT CIRCULATION: FRITZ ZAUCKER.

a. Zaucker, F. and W.S. Broecker, *The influence of atmospheric moisture transport on the fresh water balance of the Atlantic drainage basin: GCM simulations and observations*, *Jour. Geophys. Res.*, **97**, 2765:2774, 1992.

Abstract: An attempt has been made to evaluate the reliability of water vapor transport estimates from atmospheric general circulation models (GCMs) by comparing the vapor export from the Atlantic basin obtained using the GISS 4° X 5° grid GCM with that obtained from observations of wind velocity and humidity [Oort, 1983]⁸. We find substantial differences. The model gives an export of 0.13 Sverdrups (Sv) from the Atlantic basin compared to 0.32 Sv from the Oort data set. We note that the GCM produces far stronger easterly winds and correspondingly larger tropical vapor transports. Further, because of the model's low orography, steering of the winds and drying of air masses by mountain chains are not adequately

⁸ Oort, A. H., Global atmospheric circulation statistics, 1958-1973, NOAA Prof. Pap. 14, 1983.

represented. This leads to a dramatic overestimation of water vapor transport across mountain ranges. In an additional model experiment, we calculated the water vapor transports in a double- CO_2 scenario. We find that atmospheric freshwater loss from the Atlantic basin is increased to 0.30 Sv compared to 0.13 Sv in the control run. Because of the deficiencies of the model mentioned above, however, we conclude that estimates of vapor transport for future greenhouse conditions and past glacial conditions made using GCMs have to be taken with great caution until models with more realistic flow patterns, especially around mountain ranges, are available.

- b. Zaucker, F., T.F. Stocker, and W.S. Broecker, *Atmospheric freshwater fluxes and their effect on the global thermohaline circulation*, Jour. Geophys. Research, Special Issue on North Atlantic Deep Water Formation: Observation and Modeling, **99(C6)**, 12,443:12,457, 1994.

Abstract. Atmospheric water vapor fluxes were derived from a 1-year data set of horizontal wind speed and specific humidity assimilated from meteorological observations by the European Center for Medium-Range Weather Forecast (ECMWF). Vertically integrated horizontal freshwater fluxes were compared to those of two data sets based on a climatology [Oort, 1983]⁹ and on simulations with an atmospheric general circulation model (AGCM). Zonal transports agree fairly well at all latitudes outside the tropics, where fluxes are about double for the AGCM data set. Meridional fluxes of the AGCM and ECMWF data sets show close agreement, while the climatological fluxes are generally smaller with a considerable northward shift in the southern hemisphere. Atmosphere-to-ocean freshwater fluxes were derived from the three data sets. Not only is there substantial disagreement between the data sets, but their zonal averages over the Atlantic, Pacific, and Indian Ocean basins show little resemblance to the respective restoring freshwater fluxes from a 2-dimensional ocean model. If the ocean model is forced with the observed and modeled atmospheric fluxes, we find that the mode of ocean circulation is

⁹ Oort, A. H., Global atmospheric circulation statistics, 1958-1973, NOAA Prof. Pap. 14, 180 pp., U.S. Gov. Print. Office, Washington, D.C., 1983.

determined mostly by the net flux to the high-latitude oceans and the amount of freshwater exported from the Atlantic basin. The latitudinal structure of the freshwater fluxes in low-latitudes and midlatitudes has little influence on the modeled thermohaline circulation. The fluxes derived from the climatology and ECMWF permit North Atlantic Deep Water (NADW) formation, but a strong freshwater input to the Southern Ocean inhibits Antarctic Bottom Water formation. The AGCM transports so much moisture to the Arctic Ocean that NADW formation is shut down, resulting in a ocean circulation mode of southern sinking in all three ocean basins. If NADW is formed in the model, the strength of the Atlantic meridional overturning is determined by the net freshwater export from the Atlantic basin. When this export is artificially increased in the model over a range from 0.2 to 1 Sv, the ratio of overturning to freshwater forcing decreases almost linearly.

4. NOBLE GAS PALEOTEMPERATURES: JORDAN CLARK.

- a. Stute, M., P. Schlosser, J.F. Clark, and W.S. Broecker, Paleotemperatures in the southwestern United States derived from noble gases in ground water, *Science*, **256**, 1000:1002, 1992.

Abstract. A paleotemperature record based on measurements of atmospheric noble gases dissolved in ground water of the Carrizo aquifer (Texas) shows that the annual mean temperature in the southwestern United States during the last glacial maximum was about 5°C lower than the present-day value. In combination with evidence for fluctuations in mountain snow lines, this cooling indicates that the glacial lapse rate was approximately the same as it is today. In contrast, measurements on deep-sea sediments indicate that surface temperatures in the ocean basins adjacent to our study area decreased by only about 2°C. This difference between continental and oceanic records poses questions concerning our current understanding of paleoclimate and climate-controlling processes.

- b. Stute, M., J.F. Clark, P. Schlosser and W.S. Broecker, *A 30,000 yr continental paleotemperature record derived from noble gases dissolved in groundwater from the San Juan Basin, New Mexico*, Quaternary Research, **43**, 209:220, 1995.

Abstract: Paleotemperatures for the last glacial maximum (LGM) have been derived from noble gases dissolved in ^{14}C -dated groundwater of the Ojo Alamo and the Nacimiento formations in the San Juan Basin, northwestern New Mexico. The difference in mean annual (ground) temperature between the Holocene and the LGM was determined to be $5.5 \pm 0.7^\circ\text{C}$. A practically identical result, $5.2 \pm 0.7^\circ\text{C}$, has been obtained previously from the Carrizo aquifer in southern Texas. This suggests that the southwestern United States was uniformly cooler during the LGM and that the mean annual temperature gradient along a transect from the Gulf of Mexico to northwestern New Mexico has been unchanged since the LGM. The noble gas paleotemperatures are supported by paleoecological evidence in the region. The Holocene/LGM temperature difference of 5.4°C indicates that a simple lapse rate calculation may be applied to convert the 1000-m glacial depression of snowlines in the Colorado Front Range into a temperature decrease. A continental temperature change of $5.4 \pm 0.7^\circ\text{C}$ is inconsistent with a temperature change of about 2°C determined for the surface waters of the Gulf of Mexico.

5. FATE OF TRITIUM PRODUCED DURING ATMOSPHERIC TESTING OF NUCLEAR WEAPONS: RANDY KOSTER.

- a. Koster, R., W.S. Broecker, J. Jouzel, B. Suozzo, G. Russell, D. Rind, J.W.C. White, *The global geochemistry of bomb produced tritium; general circulation models compared to the real world, accepted*, Jour. Geophys. Res., **94**, 18,305:18,326, 1989.

Abstract: Observational evidence suggests that of the tritium produced during nuclear bomb tests that has already reached the ocean, more than twice as much arrived through vapor impact as through precipitation. In the present study, the Goddard Institute for Space Studies $8^\circ \times 10^\circ$ atmospheric general circulation model is used to simulate tritium transport from the upper atmosphere to the ocean. The simulation indicates that tritium delivery to the ocean via vapor

impact is about equal to that via precipitation. The model result is relatively insensitive to several imposed changes in tritium source location, in model parameterizations, and in model resolution. Possible reasons for the discrepancy are explored.

- b. Jouzel, J., R.D. Koster, R.J. Suozzo, G.L. Russell, J.W.C. White, and W.S. Broecker, Simulations of the H_2O and H_2^{18}O atmospheric cycles using the NASA/GISS General Circulation Model: Sensitivity experiments for present-day conditions, *Journal of Geophys. Research*, **96(D4)**, 7495:7507, 1991.

Abstract. Incorporating the full geochemical cycles of stable water isotopes (HDO and H_2^{18}O) into an atmospheric general circulation model (GCM) allows an improved understanding of global δD and $\delta^{18}\text{O}$ distributions and might even allow an analysis of the GCM's hydrological cycle. A detailed sensitivity analysis using the NASA/Goddard Institute for Space Studies (GISS) Model II GCM is presented that examines the nature of isotope modeling. The tests indicate that δD and $\delta^{18}\text{O}$ values in nonpolar regions are not strongly sensitive to details in the model precipitation parameterizations. This result, while implying that isotope modeling has limited potential use in the calibration of GCM convection schemes, also suggests that certain necessarily arbitrary aspects of these schemes are adequate for many isotope studies. Deuterium excess, a second-order variable, does show some sensitivity to precipitation parameterization and thus may be more useful for GCM calibration. Due to strong sensitivity over polar regions, GCM isotope modelers must choose carefully the numerical scheme for isotope transport and the formulation of kinetic fractionation processes at snow formation. The GCM results support the assumption that isotope fractionation does not occur during evaporation over continental areas.

6. SOIL HUMIC TURNOVER TIMES: K. HARRISON AND R. RUTBERG.

- a. Broecker, W.S., G. Bonani, C. Chen, E. Clark, S. Ivy, M. Klas, T.-H. Peng, *A search for an Early Holocene CaCO_3 Preservation Event*, *Paleoceanography*, **8**(3), 333:339, 1993.

Abstract. The CO_2 record for air bubbles from the Byrd Station ice core suggest a drawdown in the ocean-atmosphere carbon reservoir during the early Holocene. Such a drawdown would require a corresponding increase in the $\text{CO}_3^{=}$ ion concentration in the deep sea. We report here the results of a search in Atlantic sediments for evidence that the lysocline showed a corresponding deepening. While both the pteropod and the calcite preservation records we have obtained are consistent with expectation, they are not conclusive.

- b. Harrison, K., W.S. Broecker, G. Bonani, *The effect of changing land use on soil radiocarbon*, *Science*, **262**, 725:726, 1993.

Abstract. Most carbon budgets require greening of the terrestrial biosphere as a sink for some of the excess carbon dioxide produced by fossil fuel burning and deforestation. Much of this storage is thought to occur in soils, but running counter to this conclusion is the observation that cultivation has reduced the agricultural reservoir of soil humus. Radiocarbon measurements in agricultural soils lend support to this browning of agricultural lands. Moreover, the loss is from the fast cycling portion of the humus.

- c. Rutberg, R.L., D.S. Schimel, I. Hajdas, and W.S. Broecker, *The effect of tillage on soil organic matter using ^{14}C : A case study*, *Radiocarbon*, **38**(2), 209:217, 1996.

Abstract. We compared four adjacent soil plots in an effort to determine the effect of land use on soil carbon storage. The plots were located at the High Plains Agricultural Research Laboratory near Sidney, Nebraska. We measured ^{14}C , total carbon, total nitrogen and ^{137}Cs to determine the size and turnover times of rapid and stable soil organic matter (SOM) pools, and their relation to land-use practices. Results were consistent with the model produced by Harrison, Broecker and

Bonani (1993a)¹⁰ in that the ¹⁴C surface soil data fell on the time trend plots of world ¹⁴C surface soil data, indicating that the natural sod and non-tilled plots had a rapidly turning over SOM pool, comprising *ca.* 75% of surface soil carbon, and the tilled plots had a rapidly turning over SOM pool, comprising only 50% of surface soil carbon.

¹⁰ Harrison, K. G., Broecker, W. S. and Bonani, G. 1993a The effect of changing land-use on soil ¹⁴C. *Science* 262: 725-726.